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MEASUREMENTS ON STANDARDS OF RADIATION IN ABSOLUTE VALUE

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One of the chief needs in the measurement of radiant energy is a convenient standard against which the radiometer may be calibrated. Another desideratum is a simple radiometer the receiver of which is continuous (that is, has no openings or perforations in it), and which will thus intercept all the radiant energy within a given area. The surface of such a receiver may be rendered completely absorbing, to within 1.5 to 2 per cent, by smoking it. Then, if the flux of energy at a given distance from the standard radiator and the area of the radiometer exposed are known, it is an easy matter to calibrate the instrument in such a manner that one experimenter's work can be reproduced by another. As a convenient and very sensitive radiometer, the bismuth-silver thermopile with such a continuous receiver has been found to fulfill the requirements, and the latest developments in this line will be given in a forthcoming paper. In the present paper only the standards of radiation will be considered.

THE HEFNER LAMP

One of the earliest attempts to establish an absolute standard of radiation was made by Ångström [1] who determined the radiation from the Hefner lamp. In his earliest work he placed a screen, having an opening of 14 by 40 mm, at a distance of about 10 cm in front of the flame, which was kept burning at a height of 40 mm. Unfortunately, in his subsequent papers no further reference is made to this diaphragm, and the general custom now seems to prevail to use the Hefner lamp without a diaphragm, just as it is used in photometry. The result is that the radiation

[1] Ångström: Wied. Ann., 67, p. 633, 1899; Phys. Zs., 3, p. 257, 1902; Phys. Rev., 17, p. 302, 1903.

from the nonluminous gases above the flame adds about 18 per cent to the radiation received through the 40 by 14 mm slit, as defined by Ångström. Hence, the calibrations of radiometers made in terms of the Hefner lamp without the diaphragm are in error by about 18 per cent.

The value of the intensity of the radiation (presumably passing through the 40 by 14 mm slit, although no mention is made of it in the later measurements) as determined by Ångström with an electrically compensated pyrheliometer, at a distance of 1 m from the lamp, is 21.5×10^{-6} g–cal. per square centimeter per second. No correction was made for reflection. Applying this correction (2 per cent) makes Ångström's value 21.9×10^{-6} g–cal. per square centimeter per second.

A new determination of this constant has recently been made by Gerlach [2] with a modified form of Ångström pyrheliometer. He limited the radiation from the Hefner flame by placing a diaphragm having an opening 50 by 14 mm, at a distance of 10 cm from the flame. The lower edge of the opening in the diaphragm extended about 5 mm below a horizontal line through the top of the tube holding the wick, and, hence, extended 5 mm above the flame as measured by Ångström. He examined amyl acetate from various sources, and used different lamps. Under these conditions he found values of 21.7 to 22.7×10^{-6} g–cal. per square centimeter per second for the radiation at a distance of 1 m from the Hefner lamp. The predominating values are 22.5 to 22.6×10^{-6} g–cal. per square centimeter per second which, when corrected by 2 per cent for loss by reflection from the receiver, gives a mean value of about 23.0×10^{-6} g–cal. per square centimeter per second. In view of the fact that Gerlach's determinations were made with an instrument which gave him a high value for the constant ($\sigma = 5.90 \times 10^{-12}$ watt. cm^{-2} $deg.^{-4}$) of total radiation of a black body, the accuracy of these measurements remains to be determined. It also remains to be decided whether it is worth while to attempt to attain a higher accuracy, for it is known that the candlepower varies with the atmospheric humidity, and it is probable that the total radiation also varies with the humidity.

[2] Gerlach: Phys. Zs., 14, p. 577; 1913.

The variation in humidity has, no doubt, the greatest effect by absorbing infra red radiation. Gerlach found no marked difference in his values for different lamps and for pure amyl acetate.

In view of the fact that the Hefner lamp is a convenient standard, and in some cases is sufficiently accurate when properly used, it was compared directly against a black-body radiator which is being used in the determination of radiation constants. The standard incandescent lamps to be mentioned presently and the flame standards were compared on the same day. The absolute value of the radiation, as given, is based upon the constant of total radiation $\sigma = 5.7 \times 10^{-12}$ watt. cm^{-2} deg.$^{-4}$, which is practically the mean value of the best present-day determinations of this constant.

On account of the high sensitivity of the radiometers now available, which gives excessively large deflections when the standard of radiation is at a distance of 1 m, the present measurements were made with the radiometer situated at a distance of 2 m from the center of the wick tube of the lamp. The inverse square law is then applied to obtain the value at the conventional distance of 1 m, on the assumption that the atmospheric absorption is negligible and that the opening in the diaphragm represents a point source. Under these conditions the radiation of the Hefner lamp, with and without a diaphragm (at a distance of 10 cm from the flame), is given in Table 1. It is desirable, however, to make the measurements at a distance of 2 m.

TABLE 1

Radiation from Hefner Lamp and Standard Sperm Candle

Opening in diaphragm	Radiation per cm^2 at 2 m		Radiation in g-cal. per cm^2 per sec. at 1 m
	Watt	Gram calorie per second	
14 by 40 mm	23.1×10^{-6}	5.5×10^{-6}	22.0×10^{-6}
14 by 50 mm	24.2×10^{-6}	5.8×10^{-6}	23.2×10^{-6}
No diaphragm	27.2×10^{-6}	6.5×10^{-6}	26.0×10^{-6}
Sperm candle: No diaphragm	30.5×10^{-6}	7.3×10^{-6}	29.2×10^{-6}

In the present work the diaphragm, with an opening 14 by 50 mm, was placed at a distance of 10 cm from the flame. The lower edge of the opening was placed on a level with the top of the German-silver tube which holds the wick. The upper edge was formed by a movable cover which could be lowered, thus forming openings 50, 45, 42, and 40 mm in height. The center of the receiver was placed at the same height as the center of the opening in the diaphragm.

The radiation passing through the opening 42 mm in height was about 0.9 per cent greater than that passing through the opening 40 mm in height. Using no slit, the radiation (observed at 1.2 m from the flame) was 18 per cent higher than that observed through the slit opening of 14 by 40 mm. The precision attained in these preliminary measurements was not so high as in subsequent work. The precision attained in the final measurements may be judged from the three sets of measurements of the radiation from the flame (having no diaphragm) made on different days, the lamp having been reset in the meantime. The departure of these three values (26.09, 26.00, and 26.03; mean value $= 26.04 \times 10^{-6}$ g-cal. cm^{-2} $sec.^{-1}$ at 1 m) from the mean is far less than is ordinarily found in radiometric work. A similar series of observations made in July, 1913, having the lamp at 1.2 m, gave a value which was over 2 per cent higher.

These measurements were made in the winter when the moisture content in the atmosphere was low. Owing to the variable absorption of atmospheric water vapor in the infra-red, the Hefner lamp can not be considered a standard for high precision in stardardizing radiometers. As already mentioned, the present measurements were made at a distance of 2 m, since that is a convenient distance from sensitive radiometers. Because of atmospheric absorption in the infra-red and of the fact that the diaphragm opening does not represent a point source, the inverse square law can not be rigorously correct, so that if measurements are made at, for example, 2 m, then reduced to a distance of 1 m, the value thus found is smaller than the one observed directly at a distance of 1 m. For example, the radiation from this lamp with a diaphragm opening of 14 by 50 mm, determined seven months

ago (July, 1913), at a distance of 1.2 m gave a value of 24.5×10^{-6} g-cal. cm^{-2} $sec.^{-1}$ at 1 m. The radiation through the 14 by 40 mm opening was then 23.3×10^{-6} g-cal. cm^{-2} $sec.^{-1}$. These absolute values determined at the shorter distance are, respectively, 5.6 and 5.9 per cent higher than those observed at 2 m and reduced to the conventional distance of 1 m.

Gerlach's data show a similar deviation from the inverse square law. His values, reduced to a distance of 1 m, are of the order of 23.1×10^{-6} g-cal. when the lamp stood at 0.86 m. from the receiver, and of the order of 21.8×10^{-6} g-cal. when the lamp was distant 2 m. This is a systematic difference of about 5 per cent in his results, which is in agreement with present observations. That it is not greater is no doubt owing to the use of the diaphragm having an opening 14 by 50 mm, which shields the thermopile from the hot gases above the flame, for the radiation from these hot gases (CO_2 and water vapor), situated a short distance above the luminous portion of the flame, would suffer most by absorption in traversing the 2 m of air.[3]

In order, therefore, to give a reasonably accurate statement of the sensitivity of a radiometer, in terms of the radiation from a flame standard of radiation it is important to use the lamp as specified. Using a diaphragm with an opening 14 by 50 mm, situated at a distance of 10 cm from the flame, the value of the radiation of the Hefner lamp may be taken to be 23×10^{-6} g-cal. per square centimeter per second at 1 m without reference to the humidity, when an accuracy not higher than 5 to 6 per cent is desired. If a more reliable measurement is to be made, a seasoned incandescent lamp, which has been calibrated against a black body, should be used.

THE STANDARD SPERM CANDLE

The so-called standard sperm candle is often employed in radiation sensitivity tests, but its use is to be discouraged because of the great fluctuations in its burning. The mean value for different candles was found to be fairly constant, but in any one candle the maximum to minimum fluctuation in radiation varied by 18 to 20

[3] For data and references to the great opacity of CO_2 and water vapor in the infra-red, see this Bulletin 7, p. 619; 1911.

per cent. The total radiation at a distance of 2 m from the radiometer was observed for over an hour. No diaphragm was used in front of the flame. It was easy to see when the burning was far above or below "normal." The mean value of the galvanometer readings was taken when the deflections were fairly constant. The average radiation from a standard sperm candle, at a distance of 1 m was found to be 29×10^{-6} g-cal. per square centimeter per second. The radiation from the standard candle is therefore about 12 per cent higher than that from the Hefner lamp. This is a little higher than the photometric ratio, as one would expect, since the red-hot wick contributes but little light but it emits infra-red radiations.

CARBON INCANDESCENT LAMP STANDARDS

The great utility of a seasoned carbon incandescent lamp as a photometric standard is well recognized; and such a lamp has every desideratum of a standard of radiation, when calibrated against a black body as the primary standard of radiation. If a series of incandescent lamps be calibrated against a black body and preserved by the national laboratories, it will be a simple matter for an experimenter to have the radiation from his standard incandescent lamp certified in terms of these lamps, thus obtaining a calibration in absolute value. With such a lamp higher precision may be attained than is possible with flame standards. The radiation, which is transmitted by the glass bulb of the lamp, being of wave lengths less than 3.5 μ, is affected but little by variations in atmospheric humidity, and hence no correction for atmospheric absorption will be necessary. The radiometer surfaces are sufficiently nonselective in their absorption, so that a more reliable calibration is to be expected from an incandescent lamp whose spectrum terminates at 3.5 to 4.0 μ, than from any form of radiator which emits an appreciable amount of radiation of wave lengths greater than 4 μ. No diaphragm is used in front of the lamp, which has lines etched upon it to insure proper orientation.

The main precautions to be taken in using a radiation standard are: (1) To have a black cloth about 1 m to the rear of the lamp to prevent reflection of radiation from the wall; (2) to observe

the amount of radiation from the walls to the radiometer (or from the radiometer to the walls) when the shutter is raised from in front of the lamp before it is lighted; and (3) to operate the lamp about 10 minutes to thoroughly warm the inner parts before making readings.

The comparison of the incandescent lamps against a black body is not made without some difficulties, but from the results given in Table 2 it will be noticed that a high precision is attainable. In fact, the deviations from the mean value are due chiefly to inaccuracies in the determination of the galvanometer sensitivities on different days. Using a potentiometer device this inaccuracy would be eliminated.

TABLE 2

Observations on Incandescent Lamp C_1, with Thermopiles Calibrated Against a Black Body

[The energy is given in watts per mm² × 10^{-8} and the per cent deviation, "dev.," from the mean value]

Uncorrected amps.	Pile No. 23 Calibration July 9, 1913 Observations July 9, 1913		Pile No. 21 Calibration July 9, 1913 Observations July 9, 1913		Pile No. 25 Calibration July 22, 1913 Observations July 22, 1913		Pile No. 25 Calibration July 22, 1913 Observations July 31, 1913		Mean value
	Watts×10^{-8}	dev.	Watts×10^{-8}	dev.	Watts×10^{-8}	dev.	Watts×10^{-8}	dev.	Watts×10^{-8}
0.45	.....	.....	.....	.....	115.8	+0.13	115.5	−0.13	115.65
.4385	109.75	+0.69	108.25	−0.69	.....	.....	.....	.....	109.00
.42	100.50	+ .76	99.27	− .47	99.40	− .34	99.77	+ .03	99.74
.40	89.78	+ .60	88.96	− .22	88.76	− .42	89.23	+ .05	89.18
.38	79.96	+ .11	80.00	+ .16	79.63	− .30	79.88	+ .01	79.87
.35	67.37	+ .52	67.03	+ .01	66.58	− .66	67.08	+ .09	67.02
.30	.....	.....	.....	.....	.....	.....	48.23	.....	48.23

The method of observation consisted in exposing the thermopile alternately to a black body radiator and to the standard lamps. In order to determine the "constants" of the thermopile the distance from the black body was varied; water-cooled shutters and diaphragms of known apertures were used; the black body was heated at different temperatures from 700° to 1200° C, and all the rules were observed for the operation of such a radiator. The constant of radiation was taken to be $\sigma = 5.7 \times 10^{-12}$ watts per square centimeter, and the value of 1 mm deflection (the

"constant" of the thermopile used) was determined in terms of radiation in absolute value for a given galvanometer sensitivity. For example, using a galvanometer sensitivity of $i = 5 \times 10^{-10}$ ampere, the "constant" of thermopile No. 10 was 1 mm deflection $= 4.15 \times 10^{-8} \pm 0.03$ watt, and of thermopile No. 21, 1 mm deflection $= 6.28 \times 10^{-8} \pm 0.05$ watt. Usually the comparison of the thermopile was made against the black body and the incandescent lamp on the same day, before the galvanometer sensitivity and other conditions could change. In the later observations, Table 2, in which greater care was taken in determining the galvanometer sensitivity, a precision of a few parts in one thousand was attained; and if there were a demand for it, a still higher accuracy could be attained by taking certain minor precautions not ordinarily observed.

The intercomparison of two incandescent lamps is an easy matter. For example, after a lapse of about seven months two standard incandescent lamps were intercompared, the one lamp having been used considerably in the meantime. The lamps were operated on 0.4 ampere, on which current the ratio of their energy emission, as read from the calibration curves, was supposed to be 1.079. The ratio of the energy radiated, as observed with a thermopile (in air, no window, area exposed 1.833 by 14.415 mm), was 1.082, which is a deviation of 0.3 per cent. That the precision attained was not higher was owing to the fact that the measurements were made on a windy day, when air currents caused unsteadiness in the deflections; and also owing to a difference in the temperature of the shutter (in front of the lamp), the thermopile, and the walls of the room, which affected the deflections by 0.12 cm, with an uncertainty of 0.02 to 0.03 cm. Subsequent to this test about a dozen incandescent lamps were intercompared radiometrically. The values of energy emitted were found in agreement by 1 to 3 parts in 1000 with the direct calibration made six months ago, which was as close as the calibration curves could be read.

SPECIFICATION OF RADIOMETER SENSITIVITY

The specification of the sensitivity of a thermopile in terms of "microvolts per microwatt" of radiant power, or a similar notation, is not complete. In a forthcoming paper it will be shown that the

joint sensitivity of a thermopile and galvanometer to radiation is not seriously decreased (this decrease amounts to about 5 per cent) by having the external resistance twice as great as the internal resistance; a greater difference will hardly occur in practice. It will be shown, also, that the radiation sensitivity of the thermopile is as much a question of nicety of construction as it is of the number of thermoelements, and of the thermoelectric power per element. It seems sufficient, after specifying the current sensitivity of the Thomson galvanometer, to state the deflection produced per microwatt of radiant power incident upon the receiver of specified area. This will be necessary if calibrated incandescent lamps be used. In this manner the thermopile serves merely as an intermediary in comparing the intensity of a radiation ("light") stimulus with that of a standard of radiation.

The custom of specifying the radiation sensitivity in terms of the total radiation received from a standard flame per square centimeter of area of the receiver exposed at a distance of 1 m is useful and, on the assumption that the constant of total radiation of a black body is $\sigma = 5.7 \times 10^{-12}$ watt cm^{-2} $deg.^{-4}$, the following relations are given:

Source	Radiation
1 sperm candle	29 microcalories per centimeter.
1 Hefner unit	26 microcalories (no diaphragm).
1 Hefner unit	23 microcalories (diaphragm with opening 14 by 50 mm).
1 microcalorie	0.034 sperm candle.
	0.0385 Hefner unit (no diaphragm).
	0.043 Hefner unit (diaphragm with opening 14 by 50 mm).

In conclusion, it is desirable to emphasize the importance of specifying the intensity of a radiation stimulus in accurate units so that an experimenter's work can be repeated. For example, in photo-electric work, in stimuli applied to the eye, in experiments on the variation of sensitivity of selenium with intensity of the stimulus, in photostimuli as affecting plant growth, and in photochemical reactions in general it is desirable to specify accurately the mechanical equivalent of the stimulus. By using a receiver, having a known opening, which is completely filled by the stim-

ulus radiations, it is a simple matter to expose the thermopile to a standardized lamp, and by this comparison to determine the intensity of the stimulus in absolute measure to a high degree of accuracy. In this manner a better agreement will be attained between theory and experiment, and radiometry may attain a dignity comparable with other lines of investigations.

SUMMARY

In the first part of this paper measurements are given of the radiation from the Hefner lamp and from a standard sperm candle relative to that of a black body. The data are useful for rough comparison of radiometers in absolute measures.

For refined measurements of radiation stimuli a standardized incandescent lamp is recommended for calibrating the radiometer. In the second part of this paper tabulated data are given, showing the precision attained in standardizing such an incandescent lamp against a black body by means of three thermopiles having widely different constants.

WASHINGTON, January 16, 1914.

SUPPLEMENTAL NOTE

During the past few months a series of preliminary measurements were made on the constant of total radiation ("σ") of a black body by means of a modified form of Ångström pyrheliometer. In view of the fact that this instrument will be described in a forthcoming paper on radiometers, it will be sufficient to say that the device consists of a thin strip of metal which serves both as a heater, and also as a receiver. At a short distance back of the heater-receiver is placed a linear thermopile of bismuth-silver, having a continuous receiving surface of tin. In front of the receiver are jaw slits so arranged that they may be entirely removed, thus exposing the entire width of the receiver to radiation. These slits define the width (2.5 to 5.5 mm) of the receiver which is exposed to radiation. The total length of the receiver is about 30 mm between the points where it is attached to the heavy copper terminals. Potential terminals of platinum wire 0.005 mm (also 0.025 mm) in thickness are attached at a distance of about 3 mm from the ends of the receiver. The length of the receiver which is exposed to radiation is determined by the distance (23 to 24 mm) between the potential terminals, or by slits across the ends of the receivers, with their edges directly over these potential terminals. No difference (1 part in 600 or more) could be detected in the galvanometer deflections with and without these slits across the ends of the receiver. Hence, most of the measurements were made without the slits at the ends. Measurements were made with different amounts of overlapping of radiation along the sides of the receivers.

The method of observation consists in exposing the receiver to radiation and noting the galvanometer deflection, the sensitivity of the radiometer being such that a change in temperature of 0°.1 in the black body produced a change of 1 mm in the deflections. The receiver is then heated by passing a sufficient current through

it to produce very closely the same deflection as was caused by the absorption of radiant energy. The amount of electric current flowing through the receiver heater is determined by measuring the drop in potential across a standard 1 ohm resistance. The voltage across the potential terminals is also measured. A Leeds & Northrup type K potentiometer with 0.1 shunt is used in measuring these voltages. From these two measurements the energy input is easily determined.

Two kinds of receivers were used. Those of "Therlo" (1 and 3) were 0.007 to 0.008 mm in thickness. They were painted with a mixture of lampblack and platinum black and then smoked, as described in a previous paper.[4] The reflecting power of lampblack was taken to be 1.3 per cent, which value was applied to obtain the data herewith presented. The platinum receivers (Nos. 2 and 4) were made of the thinnest material used in bolometers. Their thickness was probably less than 0.1 that of the "Therlo." They were covered electrolytically with platinum black, the reflecting power (1.4 to 1.8 per cent) of which was estimated by comparison with the samples of which the reflecting power had previously been determined.

With these instruments four series of measurements were made on the standard incandescent lamps. Measurements were, of course, made also on the black body, which was heated to about 1000° C.

The data are given in Table 3, the distance from the lamp being 2 m, as usual. The mean value (89.0) for lamp C_1, operated on 0.40 ampere, is very close to the mean value (89.18) of the previous measurements which were made on the assumption that the value of the constant of total radiation is $\sigma = 5.7 \times 10^{-12}$ watt cm^{-2} deg^{-4}. Using a more probable value of $\sigma = 5.65 \times 10^{-12}$ watt cm^{-2} deg^{-4}, the direct measurements of lamp C_1, on 0.40 ampere (see Table 2) would be 88.38×10^{-8} watt per square millimeter. These lamp standards of radiation may, therefore, be considered established with a fair degree of accuracy (0.5 per cent) without considering the value of the radiation constant, which probably will be found to be of the order of $\sigma = 5.65 \times 10^{-12}$ watt cm^{-2} deg^{-4}, or even a

[4] This Bulletin, 9, p. 283, 1913.

trifle lower than this value. A series of measurements made on this lamp (C_1 on 0.40 ampere), with an instrument constructed for nocturnal radiation work, gave a value of 89.8. In this instrument the thermopile receivers are in contact with the manganin heater-receiver.

TABLE 3

Direct Measurements in Absolute Value of the Ra diation in Watts per mm² at a Distance of 2 Meters from Standard Lamp C_1 When Operated on 0.4 Amp. (See Table 2)

Date	Receiver Area in mm²	Correction applied for reflection (Per cent)	Radiation watts $\times 10^{-8}$	Deviation from mean value	Remarks
May 15, 1914	No. 2 3.192×24.354 =77.738	1.4	89.24	+.24	Pt. Black.
May 21, 1914	No. 1 2.150×23.092 =49.649	1.3	88.56	−.44	Soot.
May 23, 1914	No. 3 4.990×24.910 =124.301	1.3	89.47	+.47	Soot.
June 2, 1914	No. 4 5.508×26.565 =146.321	1.8	88.95	−.05	Pt. Black.
June 6, 19 4	No. 4 5.49×26.565 =145.842	1.3	88.80	−.20	Pt. Black. Smoked.

Mean value=89.00

The measurements on the flame standards, having been made at the same time as those on the incandescent lamps, will not require revision, according to these direct measurements, for they are probably already a trifle high, owing to a possible systematic error which was overlooked in the discussion on a previous page. In the writer's opinion the values given herewith are as accurate as any that would be obtained on further measurements, which the flame standards do not deserve. With reference to a possible systematic error in the direct comparisons with the thermopiles, it is to be noticed that in this method of calibration the thermopiles were placed at a distance of 50 to 75 cm from the black body.

The galvanometer deflections would, therefore, be too small, owing to atmospheric absorption. The "constant" of the thermopile would, therefore, be too large, and the measurements of the radiation from the lamps would be too large. All the measurements, however, are in excellent agreement, showing that whatever the systematic errors were they were eliminated, at least within the limits of errors in making the observations.

When this investigation was undertaken there were two groups of observations on the constant of total radiation, the mean value [5] of which was closely $\sigma = 5.7 \times 10^{-12}$ watt cm^{-2} deg^{-4}.

Among the high values are the measurements of Gerlach [6], who used a radiometer somewhat similar to the one employed in the present measurements, except that he did not have the potential terminals placed upon the receiver. His value is $\sigma = 5.9 \times 10^{-12}$ watt cm^{-2} deg^{-4}.

The mean value of 50 measurements with the instrument as herein described is $\sigma = 5.61 \times 10^{-12}$ watt cm^{-2} deg^{-4}, which is practically the same as the most reliable determinations falling in the aforementioned group of low values. It may be added that the first measurements made with this instrument also gave high values ($\sigma = 6.0$ to 6.3), but after eliminating stray radiations the value decreased to $\sigma = 5.61 \times 10^{-12}$ watt cm^{-2} deg^{-4}.

In these measurements the receiver was situated at a distance of 25 to 35 cm from the water-cooled diaphragm, having an opening 4.5 mm in diameter, which was placed before the black body. The space between the receiver and the diaphragm was inclosed and kept dry with phosphorus pentoxide.

WASHINGTON, June 24, 1914.

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[5] See the writer's summary in Jahrb. Radioaktivität und Elektronik, **10**, p. 340; 1913.

[6] Gerlach: Ann. der Phys., (4) **38**, p. 1; 1912.